1 Supplementary information

1.1 Methods

The data used to fit the models is a series of two averaged virus titrations. Each titration was divided by the initial titer and the remaining model fitting was performed over the natural logarithm of the surviving proportion. Originally data contained 15, 14 and 8 measurements at 4, 22 and 56°C respectively. Due to heavy tailing with very few remaining particles in the final titrations we only used the first five measurements. The fitting procedure began with data for each temperature. We estimated parameters for the Weibull and exponential CDFs for each of the temperatures and then modelled parameter values as a response variable dependent on temperature. The resulting parameter models were substituted in both the Weibull and exponential models. Finally, we ran an additional optimization with a time-temperature coupled model (equations are below). We used normality, autocorrelation of residuals and the Akaike information criterion (AIC) to compare models. AIC's were compared with the Akaike weights test. The selected model was transformed to a differential equation. Then we generated the temperature profiles with the average minimum and maximum temperatures for each month. These profiles assume that minimum temperatures occur at 3 am and maximum at 3 pm (equations below). Simulations were run with the conditions of four locations comprising the latitudinal extremes of the spillover distribution, Cairns in far north Queensland, Kempsey in central New South Wales (southernmost part of the distribution), and Rockhampton and Redlands for the center and the hotspot of the distribution, respectively.

For spatial simulations we used a series of layers of ground temperature at zero cm depth and two shade levels, 0 and 50%, obtained from the microclim dataset (11). For each shade cover we accounted for the effect of the soil types available in microclim. The areas with the soil types of Australia were obtained from a categorical layer generated by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), from which we only distinguished the three types; soil, sand and rock. We extracted the areas with each soil type from their corresponding ground temperature layer and then merged them with its complementary layers. For simulations we assumed that shade cover did not affect minimum temperatures as these occur in the night. Each pixel of the minimum and maximum temperature layers were used as the parameters of the oscillating temperature profiles. Then we ran a simulation for every pixel in the layer and the last value of each simulation was stored in another layer. We also performed these simulations with interpolated air temperature layers (provided by BOM) to measure survival 24 h after excretion. From the resulting simulated maps we extracted the value of the pixels corresponding to the location of every event by season. Then the values of all the pixels in summer, autumn, winter and spring maps were cross tabulated to run the partial ROC test with the Partial ROC tool allowing a 20% omission rate.

1.2 Equations

Weibull model and half-life:

$$S(t) = \exp(-(\rho t)^{\kappa}) \tag{1a}$$

$$t = \frac{(-\ln S)^{\frac{1}{\kappa}}}{\rho} \tag{1b}$$

Dependence of parameters on temperature:

$$\rho(T) = \exp(\alpha_{\rho} + \beta_{\rho} T) \tag{2a}$$

$$\kappa(T) = \alpha_{\kappa} + \exp(\beta_{\kappa} T) \tag{2b}$$

Oscillating temperature profiles:

$$T(t) = a + b \times \left(\frac{1 - \cos(\pi t)}{2}\right) \tag{3}$$

In equation 3, a is the minimum temperature at 3 am and b is the difference between the minimum and maximum temperature (assumed to occur periodically at the exact same time of the day 12 h later than the minimum).

Implicit form of the Weibull probability density function:

$$\frac{dS}{dt} = -\left[\rho\kappa(-\ln S)^{1-\frac{1}{\kappa}}\right] \times S \tag{4}$$

The main disadvantage of this form of the Weibull model is that is has no solution when $S = 1$ and $\kappa < 1$. When $\kappa > 1$ and $S = 1$ simulations result in no mortality. the problem can be fixed with $S = 0.9999$ (a value very close but $S \neq 1$).

Parameters and temperature were substituted in equation 4 for simulations.

Similarly, the exponential model was coupled with the same time dependent temperature and temperature dependent parameter.

$$\frac{dS}{dt} = -\rho S \tag{5}$$

For the exponential model the equation decribing the change of parameter ρ was:

$$\rho = \exp(\alpha_\rho + \beta_\rho T^2) \tag{6}$$

1.2.1 Data

Table S 1: Data used to fit models. To obtain better fit to the initial points we only used the first five measurements of viral titres for experiments at 4 and 22 ℃. Time has been standardised to weeks, although the scale of the measurements at 56℃ was minutes. $\ln S$ is the logarithm of the surviving proportion at time T. Time units are weeks (w) and minutes (min).

Time	$\ln S$	Temperature (℃)
0 w	0	4
1 w	-0.7494845504	4
2 w	-0.6216511789	4
3 w	-1.6433024264	4
4 w	-1.4426317309	4
0 w	0	22
1 w	-4.8761644932	22
2 w	-6.4307941692	22
3 w	-7.5096038305	22
4 w	-10.2782786535	22
0 min	0	56
10 min	-7.4160777725	56
20 min	-10.2475069948	56
30 min	-12.5202391246	56
40 min	-13.8493750719	56
50 min	-13.9797368898	56
60 min	-14.2060500159	56
70 min	-14.2060500159	56

1.2.2 Parameter estimates

Values of the estimated parameters of each model.

Table S 2: Parameter values of the Weibull model. T is the value of T-student statistic and P is the significance of the parameter estimate

Parameter	Value	Std.error	T	P
α_ρ	-1.79604	0.25027	-7.176	1.81e-05
β_ρ	0.23172	0.01014	22.846	1.28e-10
α_κ	0.46812	0.03869	12.099	1.07e-07
β_κ	-0.20464	0.12488	-1.639	0.13

Table S 3: Parameter values of the exponential model

Parameter	Value	Std.error	T	*P*
α_ρ	-0.3786051	0.1221587	-3.099	0.008
β_ρ	0.0027711	0.0000467	59.333	$<$ 2e-16

1.3 Figures

Names of spillover sites across the east coast of Australia.

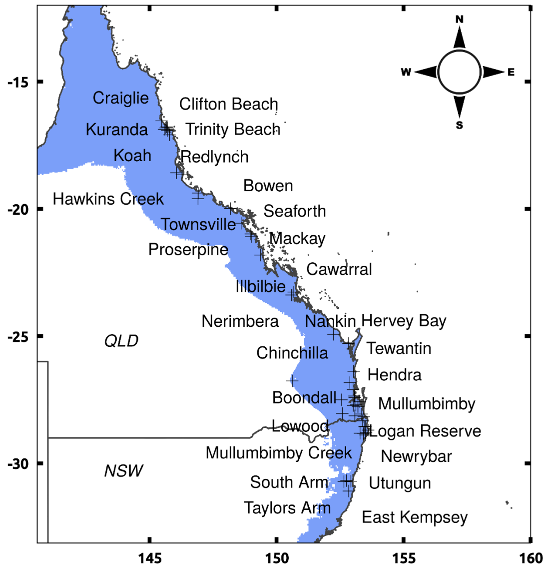

Figure S 1: Map shows the names and geographical location of spillover sites.

Difference between separate models and coupled for both the Weibull and exponential.

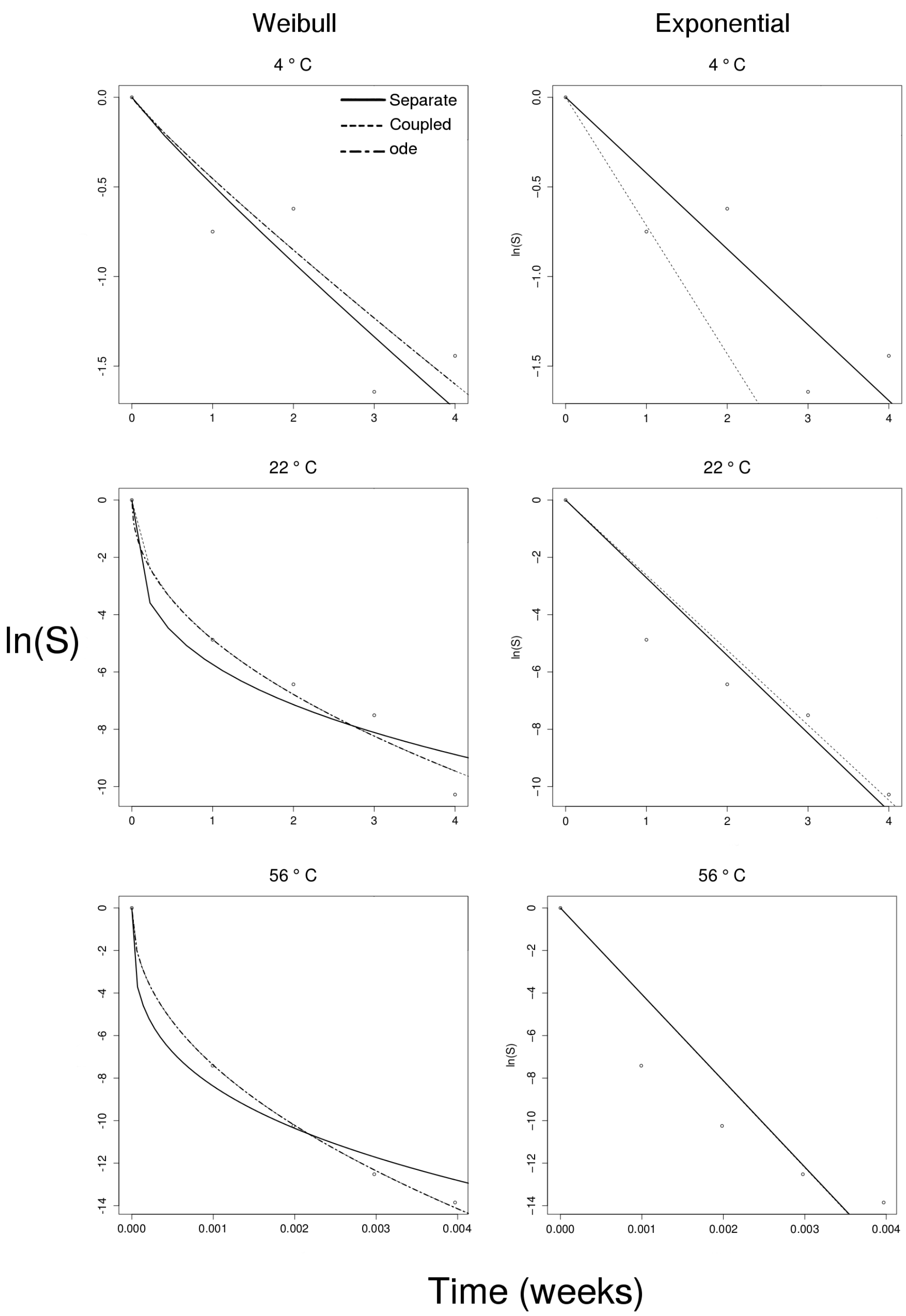

Figure S 2: Difference between fitted models. The left hand side graphs correspond to the Weibull models: the separate Weibull model fitted to individual temperatures, the coupled version of the model and the simulated version of the numerically integrated ordinary differential equation form of the coupled model.

Maps of the simulated survival with the microclim data set:

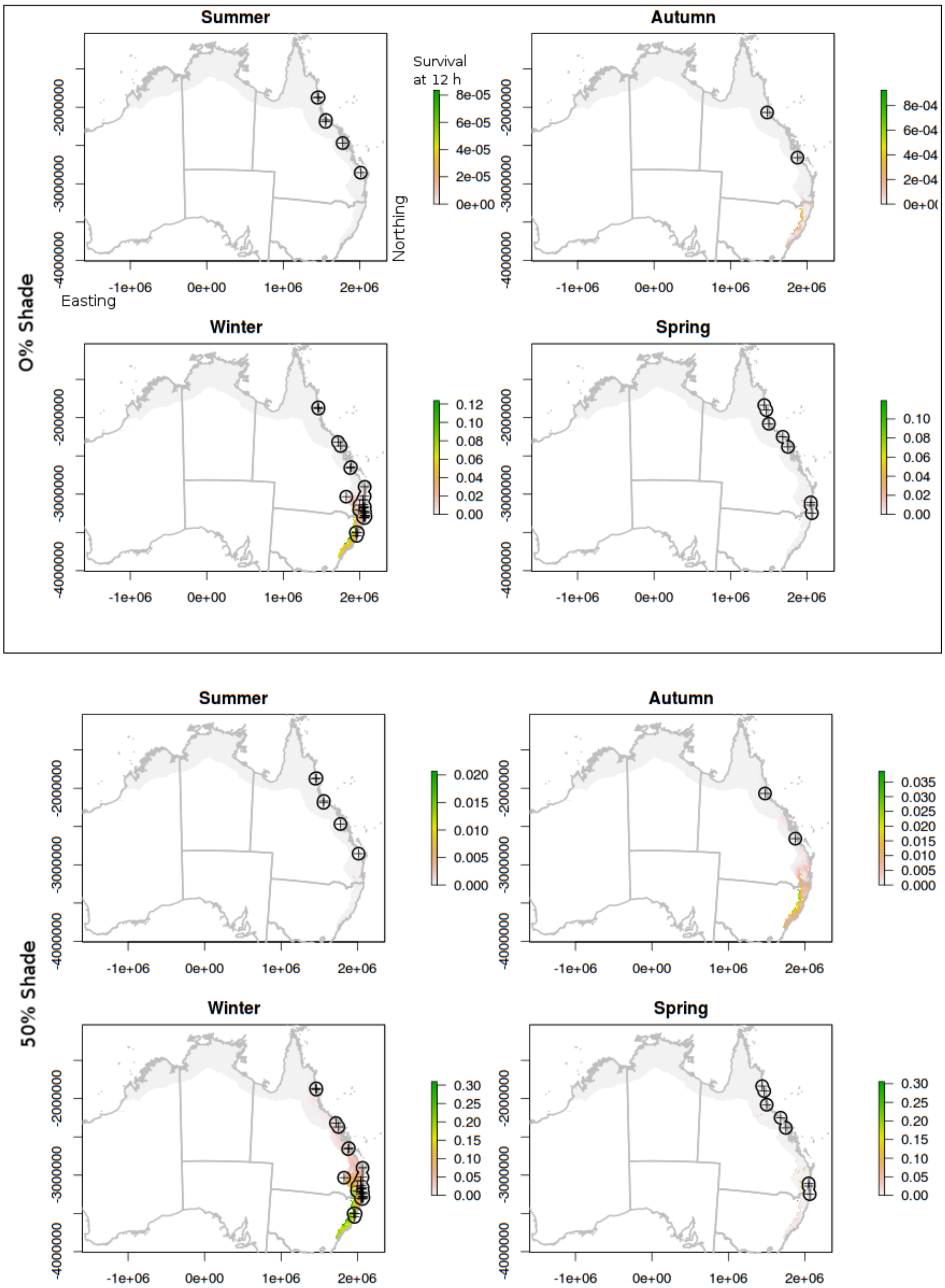

Figure S 3: The top four maps correspond to survival at ground temperature with 0% shade. The bottom four maps are under 50% shade. The temperature layers for these simulations were projected to GDA 94 datum to suit the projection of the categorical layers of the soil types of Australia, hence the different geographical coordinates, degrees and decimals in the main manuscript versus meters in this figure. Survival is estimated 12h after excretion at the minimum temperature.

Density of survival and time to 2-log reduction in ground temperature of spillover events

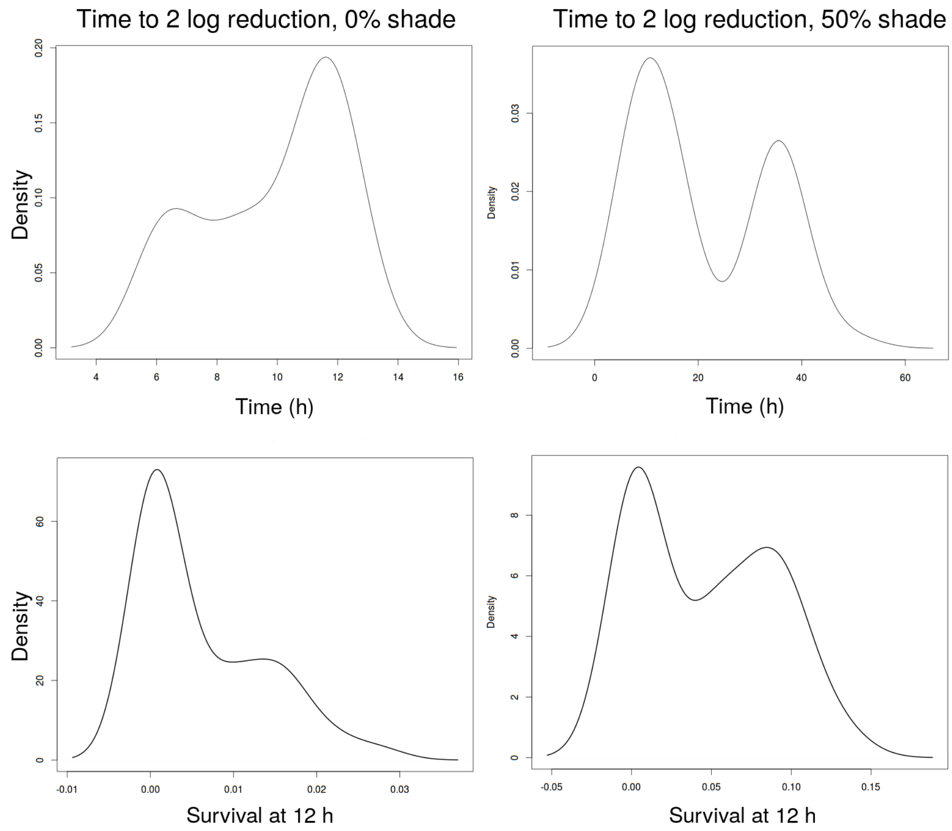

Figure S 4: Kernel density estimation of time to a 2 log reduction in live virus in ground temperatures in 0% shade (left) and 50% shade (right). The bottom densities correspond to the proportion of virus surviving 12 h after excretion.